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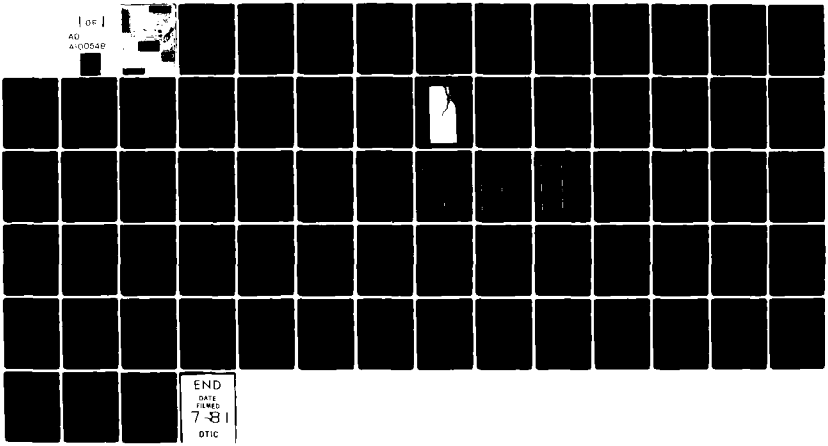

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EVALUATION OF ROCKET TRIGGERED

LIGHTNING FOR RESEARCH AND DEVELOPMENT

THESIS

AFIT/GE/EE/81J-5 Jack R. Lippert
Civilian AFWAL/FIEA

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6 EVALUATION OF ROCKET TRIGGERED LIGHTNING FOR RESEARCH AND DEVELOPMENT.

9 Master's THESIS

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by

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TABLE OF CONTENTS

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Much gratitude is expressed to the personnel of the Langmuir Laboratory operated by New Mexico Institute of Mining Technology (NMIMT), in particular Dr. C. B. Moore, without whom these experiments contained herein could not have been accomplished. A special thanks is offered to Ms. D. Hall (NMIMT) for her professional operation of the KIVA and her timely assistance with data acquisition.

Jack R Lippert

List of Figures

ABSTRACT

The feasibility of using rocket-triggered lightning as a research and development tool for testing hardware is investigated. Previous experimental work in the area is examined and used as the foundation for the experiments in this thesis to establish the significant factors of a successful lightning-triggering station. Using a point charge model, computer simulations were performed to determine the most probable locations of the charge centers associated with the triggered discharge. Five electric field records obtained from field mills were used to perform this simulation. A full scale test technique configuration is proposed for subjecting representative Air Force subsystems and components to the lightning threat. A conclusion is drawn that such a system is feasible at Mt. Baldy, New Mexico with minor augmentations of the existing facilities of the Langmuir Laboratory.

I. INTRODUCTION

The Air Force Wright Aeronautical Laboratories/Atmospheric Electricity Hazards Group (AFWAL/FIESL), sponsor for this thesis work, is the Air Force focal point for lightning effects to aircraft. As such, it is their responsibility to develop protection techniques for aerospace vehicles against the lightning threat. This threat is multi-faceted, involving both direct catastrophic damage and induced effects resulting from the varied high voltage/high current phases of a given lightning discharge. In recent years the problem has been exacerbated by increased dependence upon sophisticated electronics for mission critical and even flight critical subsystems, which appear to be susceptible to lightning effects in the 1-50 MHz range. In order to assess a system's lightning susceptibility, a means of testing it to the actual (or reproduced) threat is desired. It is towards this goal that this thesis is aimed.

Description and Terminology

To help illuminate the problem, it is beneficial to first describe the lightning discharge process. The following discussion will also establish the reference frame and terminology to be used throughout this thesis. There are two types of lightning discharges: (1) a cloud-to-ground flash and (2) an intracloud flash. Unless otherwise stated, future discussions will concern ground discharges. A succinct description presented by Uman, et al (Uman, 1978), will be paraphrased. The full lightning discharge event is called a *flash* and lasts an average of 0.5

seconds. The flash is comprised of individual discharges called strokes lasting on the order of milliseconds with the time between strokes on the order of tens of milliseconds. There are nominally four strokes per flash, but this number can vary greatly. The first stroke is initiated by a weakly luminous channel of charge called a stepped leader since it propagates in increments (or steps) of about 50 meters. When the stepped leader approaches the ground, the electric field is sufficient to cause an oppositely charged channel to emanate from the ground and propagate towards the leader. When these channels meet, a highly luminous surge of current called the return stroke travels back up the leader channel carrying ground potential into the cloud. This current is typically on the order of tens of kiloamperes. Some tens of milliseconds after the first stroke is completed, a subsequent leader/stroke process (dart leader/ restrike) may occur in the same channel of the previous stroke. During the time between strokes in the flash, small increments of charge may redistribute themselves either slowly (J-change) or abruptly (K-change) as denoted by electric field records.

The interaction of a lightning discharge with an in-flight vehicle is not fully understood and will merely by highlighted in this discussion. A vehicle flying in the environment of strong electric field would have induced charge migrating in response to the ambient field. The resultant field of the charged vehicle would tend to discharge by corona streamering and could produce a lightning strike to the aircraft. These types of direct strike lightning attachments could be part of a cloud-to-ground or intracloud lightning discharge.

Problem Definition

The problem facing the aerospace/lightning community has several parts. First, the lightning threat to which aerospace vehicle systems are exposed is not well understood. Uncertainties in magnitudes and time frames as well as different explanations for physical processes introduce variances which increase the range of possible threat inputs resulting from a lightning discharge. Addressing this part of the problem, the Air Force has an on-going program to characterize the lightning threat to in-flight aircraft.

The second part of the problem is properly simulating the threat once it is known. Present lightning simulation capabilities have many deficiencies; most notably is the limited scale to which the threat can be reproduced. Generators are capable of reproducing a given parameter of the lightning discharge but cannot duplicate at full scale all of the lightning parameters and pertinent conditions concurrently. A generator example is the FIESL Lightning Current Injection Test hardware which is capable of subjecting an aircraft to a representative lightning current waveform of average strike magnitude (30 KA), at risetimes on the order of 2 microseconds and at voltage levels of 200 KV. These values are less severe than those associated with actual lightning and analytical methods for scaling to full threat levels have not been proven. In addition, this generator is only capable of a single unipolar pulse. Many generators would be required with timed sequential firing to simulate the subsequent strokes (or restrikes) of a given lightning discharge.

Another deficiency arises from the testing facility. How severe is the impact of the facility on the simulation? The answer to this question

has not been quantified and, of course, depends on the test configuration, particular threat input, generator noise, and test object similitude. Still more subtle points concern the test implementation. It is suspected that placing the test object in a high field environment, causing it to streamer before arc attachment of the simulated threat input, would be closely representative of the actual strike case. Laboratory experiments (Butters, 1978) have shown increased electromagnetic effects when the test object is streamering and attached via an open arc (which is a strong electromagnetic noise source) as opposed to hard wiring attachment. How closely this streamering/open arc case represents the stepped leader/ arc channel is still unknown.

The final part of the problem involves proof testing. This is important for both hardening testing and verification of analytical models of lightning/vehicle interactions. Simulators of the magnitude required for this case are non-existent. This fact and lightning's unpredictability often cause items to be "proof tested" when the system is inadvertantly struck during a mission, sometimes with catastrophic results.

One possible approach to overcome these limitations is to employ rocket-triggered lightning (RTL) as a test technique. This concept uses a small rocket to deploy a thin wire between the ground and a charged thundercloud. Under sufficient conditions, lightning will be discharged through the wire between cloud and ground. Although the physics of RTL is not fully understood, triggered lightning does provide a controlled source which can be compared in magnitude and time of occurrence of the

events with natural lightning. In addition, the applied threat need not be fully characterized in advance and the RTL test can contribute data towards the understanding of that threat. Although the rocket-trigger system has its own peculiarities, "facility effects" are likely to be reduced. Therefore, such a test technique should also contribute to the understanding of the lightning/vehicle interaction process.

Purpose and Scope

The purpose of this thesis is to evaluate the feasibility of using rocket-triggered lightning as a tool for research and development investigation in the area of lightning effects. For this to be determined, the following items need to be addressed:

a) the appropriateness of rocket-triggered lightning as a threat source for hardware testing:

b) the identification of the important parameters and factors for a successful triggering station;

c) the application of the above information to a test technique configuration for subjecting hardware/components to lightning stress.

Although these points were researched, the depth of investigation was unfortunately limited by a small data point sample with some information irrevocably lost during the experimental phase of this thesis.

General Approach

This effort commenced by reviewing pertinent literature concerned with the development of rocket-triggered lightning to determine the

state of the art. An experimental phase was then conducted to identify the significant parameters and isolate potential problems of the triggered lightning concept. After analyzing results, the information learned was applied to the development of a triggered-lightning test technique proposal. The proposed configuration is an outgrowth of an AFWAL short term requirement and allows a first order attempt at full scale lightning testing of hardware.

Organization

In Chapter II the background of rocket-triggered lightning is discussed showing the developmental history of the concept and the significant advancements of the art to date. Chapters III, IV, and V are devoted to the thesis experimental phase, results, and analysis with computer simulation. A proposed rocket lightning-triggering station, satisfying the immediate needs of the AFWAL, is presented in Chapter VI. Finally, in Chapter VII, conclusions are detailed and recommendations are discussed.

II. BACKGROUND

To enhance the understanding of research in the area of triggered lightning, it is necessary to review and discuss previous efforts which have had an impact on the state of the art. Related analytical and hypothetical background will be reviewed and the pertinent experiments concerning wire/rocket triggering will be discussed. The significant experimenters whose work is directly related to that reported in this thesis are divided into three chronological as well as geographical groups: (1) Lightning and Transients Research Institute reported in the late 1960's; (2) French Office National d'Etudes et de Recherches Aerospatacles (O.N.E.R.A.) reported in the late 1970's; and (3) New Mexico Institute of Mining Technology (NMIMT) reported in the late 1970's. Since these thesis experiments were performed in conjunction with NMIMT efforts, their foundation will also be discussed in this section.

Hypothetical and Analytical Background

During the course of lightning research throughout the years, many observations have been devoted to determining the necessary conditions for a lightning discharge. Beginning with statistics of strikes to large structures (McEachron, 1941, and Hagenguth, 1952), each subsequent investigation (e.g., Ogawa, 1964, and Uman, 1964) enhanced the knowledge of the phenomena. Culmination of work atop Mt. San Salvatore (Berger, 1967) was a major achievement in the characterization of lightning from ground observations. Berger's nine years of research accumulated a data base of

6,490 natural lightning stroke statistics and measured current waveforms of both positive and negative charge of both upward and downward propagating lightning discharges. With higher and faster flying aircraft, lightning incidents appeared to be an increased problem (Fitzgerald, 1968). This precipitated more research and led some to suspect that the aircraft was not just getting in the way of a lightning discharge, but was instrumental in triggering the stroke (Shaeffer, 1972). Up to date analysis indicates that this conjecture may actually be the case (Clifford, 1980). Statistics of environmental conditions during incidents of lightning strikes to aircraft reported by Clifford, indicate a large static charging rate which develops into corona streamering from the aircraft extremities. This streamering is postulated to form a conductive wake which extends the effective conductive length of the aircraft, which in turn shorts the electric field gradient, and triggers a discharge from some charge center nearby. Airborne observations produced another avenue via which to increase the understanding of the discharge and potential triggering processes.

Small laboratory experiments performed at NMIMT (Brook, 1961) to investigate triggering phenomena used a thin wire to attempt to trigger the discharge of a long spark gap charged with a Van de Graff generator. With a stable wire suspended in the gap, a discharge would not occur due to corona current "bleeding" the charge. However, when the wire was propelled into the gap, a triggered discharge resulted showing the dynamic transient to be an important factor. Another common link between early experiments and later observations of artifically triggered lightning was the existance of an electrical field in the neighborhood of

10 KV/m and the length of the "triggering conductor" being sufficient so that the potential discontinuity between the conductors and the atmosphere approached one megavolt (Pierce, 1972). This 10 KV field/ megavolt gradient value will be later referred to as Pierce's criterion for triggering lightning.

Successful Triggering Experiments

The first lightning triggering experiments that can be considered operationally successful were those performed by Lightning and Transients Research Institute in 1965 (Newman, 1964, 1967, 1968) using rocket launched wires . The objective of these efforts was to obtain additional data for the evaluation of the lightning threat to aircraft and thereby aid development of protection measures.

The basic equipment consisted of approximately one meter long rocket pulling a fine stainless steel wire to a maximum altitude around 500 m. The other end of the wire was attached to an instrumentation platform which was connected to ground by a single current shunt arrangement, with a control spark gap for handling higher currents. The entire system was installed aboard a ship so that the surrounding ocean could provide a uniformly level ground plane (Newman, 1967).

The rocket was fired when the monitored electric field gradient was sufficiently high to indicate suitable conditions for a natural lightning discharge (nominally 10 KV/m). If a discharge was triggered, it attached to the launched wire, following the wire to the instrumentation platform and through the current shunt/spark gap to ground. Open shutter still photos and Fastax high speed motion pictures were the optical documentation.

Oscillograms of individual discharges current waveforms were obtained in both long window (≈ 1 second for detecting slow continuing current and restrikes) and short window (≈ 40 ms for examination of sharp current peak in detail).

The results of these efforts are quite significant. Using the Summer of 1966 experiment as an example, seventeen discharges were triggered with twenty-three rocket firing attempts. Thirty percent of the discharges were triggered before the rocket reached 70 m altitude. This shows that the artificial triggering of lightning can be accomplished with a reasonable degree of success to be considered for further applications. The scale and values of Newman's experiments were part of the evidence for Pierce's criterion. The wire deployment via rocket is a dynamic process which introduces transients into the E-field shown important by Brook, 1961. Close observations of the triggered discharges with still and high speed motion picture cameras revealed a lightning channel diameter of 5 cm and a violent local motion of the arc channel translating its position by as much as 2 m before the next restrike (approximately 40 msec). This channel diameter is in agreement with that obtained from fulgurites in sand (Schonland, 1950), but is larger than those from holes in fiberglas bonnets (Uman, 1964). Although these items could be observed via natural strikes to a prominent object over a period of many years, the triggering concept allows a great number of specimens for study in an abbreviated time span with a precise location and time, and this is its real significance. The major drawback of this series of experiments was the lack of coordinated data acquisition at supplemental locations to complement that obtained at close range. Since the technique

for triggering lightning is feasible, the question must be asked, how similiar is triggered lightning to naturally occurring lightning? This question will be addressed later in this thesis.

Refinements and Enhancements

The next major leap forward in triggered lightning research was experiments conducted by the French Office National d'Etudes et de Recherches Aerospatiales (O.N.E.R.A.). Originally concerned with the protection of power transmission lines and equipment, the French scientific offices jointly supported a substantial investment to construct a lightning triggering and studying facility in the Massif Central (France) community of Saint Privat D'Allier in 1973. This facility used a similar rocket-wire technique shown feasible by Newman.

The test station consists of (Fieux, 1977):

a. a 24 m tower with rocket launcher platform on top (shown in figure 1);

b. a ground level launching range;

c. a magnetic field meter with a frequency response from 150 Hz to 20 MHz recording the first peak;

d. an electric field dipole antenna with 1 KHz - 10 MHz response;

e. a 5 milliohm shunt with 86 nsec response and capable of 100 KA for discharge current measurements;

f. recorders of both DC - 10 KHz response for continuous records and 10 KHz - 3 MHz response for detail over small window; and

g. still, motion and streak cameras' (20 cm/sec) view of the discharges and oscilloscope tracings of E and B waveforms at

various distances from the launch site ranging from 200 m to 55 KM.

Rocket firing procedures are similar to Newman's in which the ground electric field potential gradient of 9 - 10 KV/m is used as firing indicator. Results similar to Newman's were achieved: 62 triggered flashes out of 89 correct firings through the 1976 season for 70% success rate vs. 75% for Newman. More recent attempts have improved that percentage of success to about 80% (Boulay, 1979). Showing that this technique can be just as successful over land where the fields are not likely to be as uniform as over water was important. However, the real significance of this continuing effort is the quality of fast data obtained by modern instrumentation with fast response (< 100 ns) and large bandwidth (> 20 MHz), and the quantity of coordinated data from various locations for the same stroke. The fast instrumentation has shown peak current risetimes typically from 0.3 to 1.5 microseconds, much faster than those that were or could be obtained by Newman. A large volume of instrumentation is needed for a comprehensive understanding of the process and to help verify theoretical calculations of lightning parameters via distant field measurements. Occasionally, a natural discharge occurred within the instrumented area. A comparison of these natural and triggered strikes has shown similar fast rising structure repeating throughout the flash, but the natural discharge has a slightly slower rise to the first peak of 1.5 - 2 microseconds (Fieux, 1978). An anomalous triggered discharge is one that does not follow the wire to ground. This kind of discharge occurred in 8 of the 62 flashes. One such anomalous flash is shown in Figure 1 with the

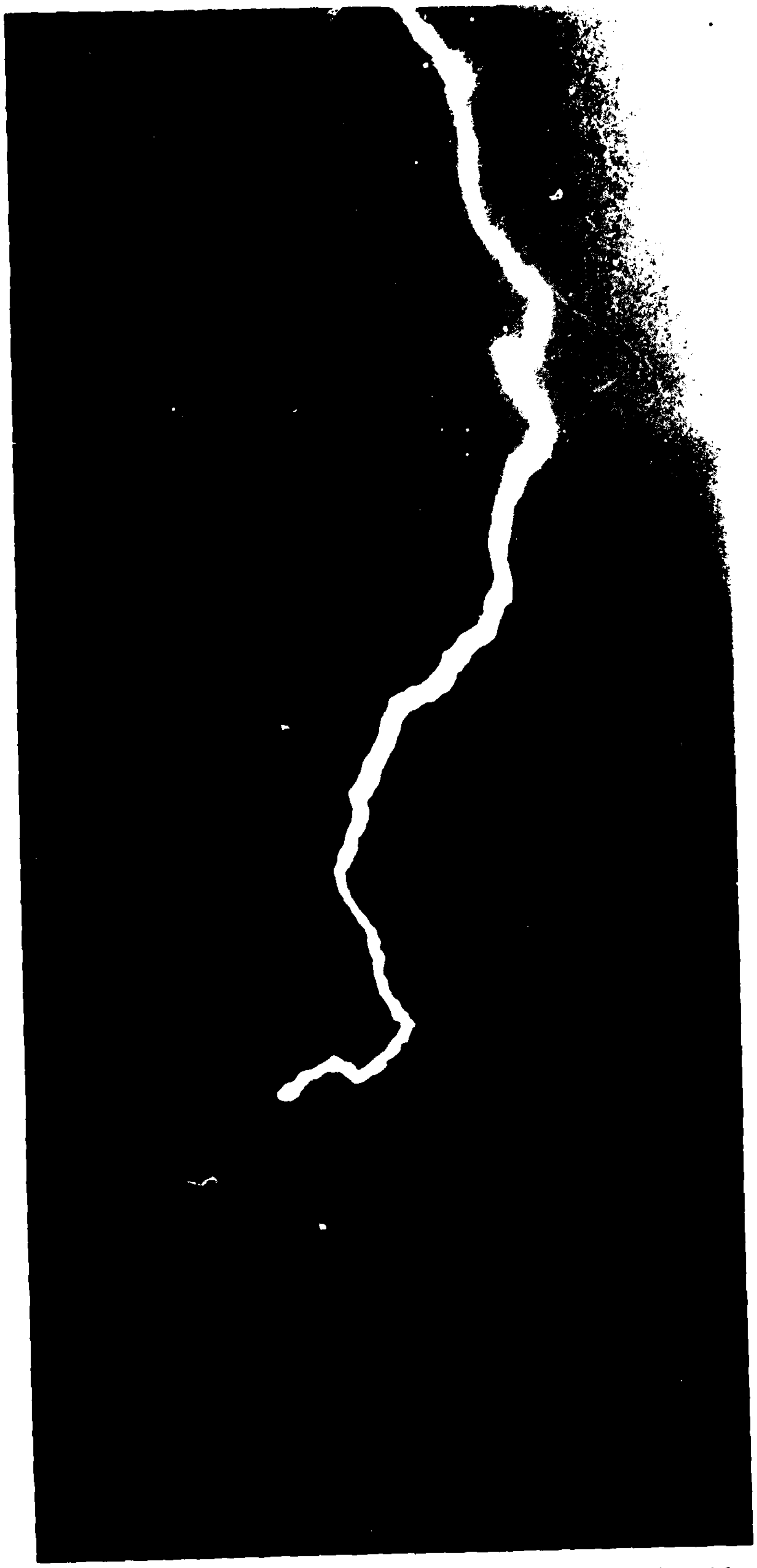


Figure. Anomalous Triggered Discharge to 24 meter Launching Platform
(Photo courtesy of Drs. Talliet, Baulay ONERA)

wire clearly visible to the left of the flash. It is obvious that the metallic wire was not the preferred path at the time. However, the French measurements show that the anomalous triggers initially draw current through the wire, melting it, as in cases for standard triggers, before the current suddenly drops to zero and the flash discharges elsewhere. No satisfactory explanation has been presented why this column of vaporized metal is not the preferred path, particularly when one of the discharges attached to the top of the wire/rocket before flashing to ground elsewhere.

As of this writing, the French station is continuing to pursue an active research program in triggered lightning studies, including support to other experimenters (Rühling, 1974), and additional contributions to this field in the near future are expected.

Thesis Experiment Foundation

The experimental work to be detailed later in this thesis was performed at the Langmuir Lab facility of the New Mexico Institute of Mining Technology (NMIMT) atop Mt. Baldy near Socorro, New Mexico. The Institute's past experience involved several attempts with different rockets and guns to propel wires for triggering lightning discharges (Moore, 1978). Most of these devices were too rapid for the wires' tensile strength, breaking them prior to sufficient deployment. Prior to 1979, only one successful triggered strike was discharged at Mt. Baldy.

Concurrent with the French early activities, a rocket/wire trigger was achieved using an ENTAC 58 rocket (Standler, 1977). Although only the initial current in the wire was measured; a comparison of the ENTAC

rocket flight characteristics with the French "Peregrelle" should provide an insight into the required processes of the triggering technique itself.

In 1979, the author participated with NMIMT and three French experimenters Drs. Boulay, LaRoche, and Eybert in rocket lightning-triggering experiments as part of the Thunderstorm Research International Program (TRIP 79). The French were invited and sponsored by NMIMT and the author's organization, AFWAL/FIESL, to set-up and fire several of their "counterhail" triggering rockets at Mt. Baldy in a similar fashion to their St. Privat d'Allier station. One standard trigger (following the wire) and one anomalous triggered discharge resulted from three firings showing comparable success percentages over mountainous terrain as over flatland or water. Only limited data was obtained during these triggered discharges and since it has been analyzed elsewhere (Baum, 1980; Boulay, 1980), it will only be highlighted in this report. These successful triggers demonstrated that the mountain site did not generally present fundamental problems to the triggering concepts.

III. EXPERIMENTAL PROCEDURE

This chapter describes the general arrangement of the experimental site and equipment used in the two storm seasons (1979-1980) atop Mt. Baldy. The 1979 set-up is discussed to accentuate the changes that were included for the following year experiment conducted as part of this thesis.

Equipment

Two different types of wire/rockets were employed during the two Mt. Baldy thunderstorm seasons discussed in this thesis. The 1979 season utilized the French "Peregrelle" or "counterhail" rocket system which is the same system used at the French station at St. Privat D'Allier (Boulay, 1979). This rocket's significant function was to elevate a single 0.2 mm diameter stainless steel wire uncoiling from a bobbin to an approximate maximum altitude of 500 m with a maximum velocity of 180 m/sec. The wire bobbin could be grounded or electrically isolated from data instrumentation prior to a triggered discharge.

Electric and magnetic field measurements were only obtained from the second of the two discharges (anomalous trigger) by standard EG&G design B dot and D dot sensors (Baum, 1978; EG&G, 1980) mounted atop an underground instrumentation station (KIVA). The magnetic field is derived by integration and vector summing outputs from two orthogonal multi-gap loop (MGL B dot model 3) sensors with a frequency response of 78 MHz, and fastest risetime < 4.5 nsec. The electric field is obtained by integration from an asymptotic conical dipole (ACD-5(R) D dot) sensor

with a frequency response of 75 MHz, and < 4.5 nsec risetime. The outputs of these sensors were input to BIOMATION 8100 transient digitizers which at their maximum sampling rate (100 MHz) had only a 20 μs window for data acquisition. Although triggered via the internal amplitude threshold mode, the BIOMATION pre-trigger option permits observing sensor output up to 5 μs before the threshold trigger. A network installed along the 2 km mountain ridge of five (5) field mills having a four blade chopper frequency of 1800 r.p.m. (120 Hz) provided the slow E-field data. The positions of the rocket launch sites and the mills at South Baldy Peak, Tower Site, Balloon Hangar, West Knoll, and Langmuir Lab are shown in Figure 2.

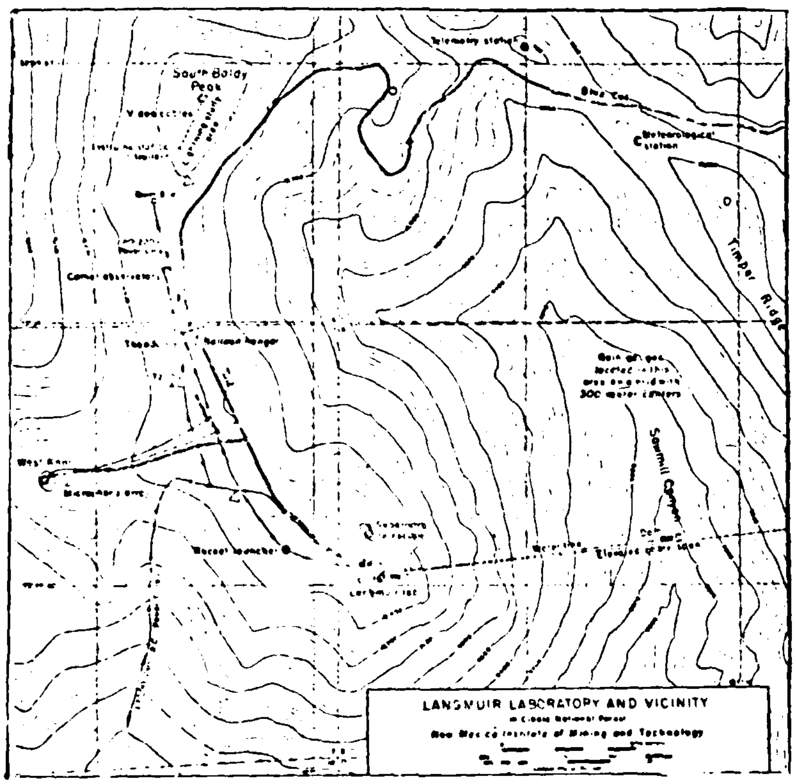


Figure 2: Map of the Mount Baldy Test Site

The "counterhail" rockets were fired from the instrumentation trailer site using the Tower Site field mill as the indicator for strong fields and, therefore, a good chance of triggering a lightning discharge.

The experiment for the following season entailed several changes, most notably the launch site was moved from the trailer site to atop South Baldy Peak, 15 meters away from the KIVA, and a different rocket type was used in the triggering attempt. Firing from the mountain peak was advantageous due to the normally higher field strength there relative to the trailer site. The rockets used were ENTAC 58s with the warhead replaced by an iron dummy. A standard ENTAC 58 is shown in Figure 3. The advantage of the ENTAC over the Peregrelle" is its internally contained wire bobbin that deploys two .2 mm steel wires which are "at rest" with respect to the surrounding atmosphere. This method reduced the chance of wire breakage and abortive trigger attempts. A disadvantage, however, is the ENTAC's slower velocity, accelerating and sustaining 180 mph (80.5 m/sec), less than half of the velocity of the "Peregrelle".

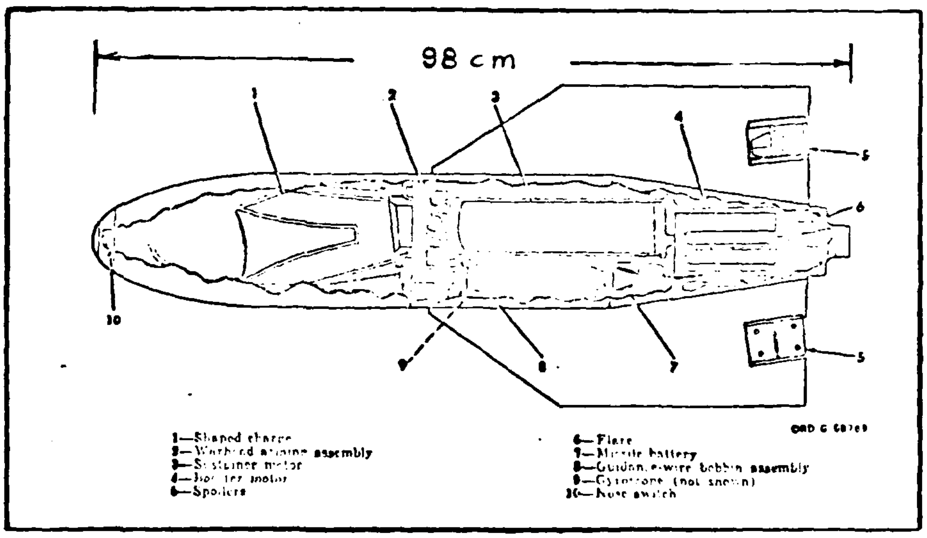


Figure 3: Diagram of ENTAC 58 Rocket

The rocket's trailing wire was grounded via 2 cm braid to a copper grounding rod driven into the ground beside the launcher. Around the braid was a Pierson Mod. 310A Current Transformer (CT) with attenuators to achieve an 8800: 1 relation of current through the CT to voltage output. The CT frequency response was 100 MHz. An E-field change meter, with an RC time constant of 0.025 seconds, was mounted atop the KIVA located southeast of the grounding rod. The CT, b dot and D dot sensor outputs were recorded on computer controlled BIOMATION 8100 transient digitizers.

A microphone was positioned at the KIVA for recording thunder instances for timing correlation. The rocket launch would also be detected by this "thundermike". The outputs from the microphone, field mills, and E-field change meter were recorded on 1 MHz FM tape. Photographic coverage was accomplished by two video tape recorders (60 frames/sec) stationed at the Balloon Hangar and Langmuir Lab buildings.

The KIVA field mill was used as the firing indicator for these attempts until the first successful trigger overloaded and destroyed the read out instrumentation. Thereafter, the rockets were fired at random since real time knowledge of the fields strength was unknown.

IV RESULTS

The raw data from the 1980 experiment is presented and interpreted in this chapter. The data are grouped into electromagnetic and optical categories.

General Results of 1980 Season

During the 1980 thunderstorm season research for this thesis, four ENTAC 58 rockets were launched in attempts to trigger lightning. The first rocket was fired during light rain and infrequent intracloud lightning. It resulted in two small discontinuities of the local field mill record, but did not trigger a visible or audible stroke to ground. The second attempt, fired during similar conditions, successfully triggered a stroke following the wire to ground. This discharge over loaded and destroyed the real time readout of the field mill used as a firing indicator. The following two attempts were fired at random during heavy rain and frequent visible lightning. No triggered discharge resulted from either of these attempts, but it was later discovered that the E-field at time of firing was relatively low (less than 6 KV/m).

Electromagnetic Fields

The E-field records for the first ENTAC firing are shown in Figures 4a and 4b. It shows the rocket being fired when the KIVA field was a stable 8.6 KV/m, and as the wire deployed elevating the "ground" potential, the E-field dropped to -6.4 KV/m (for a net change of 15 KV/m)

where the first of two discontinuities occurred. It appears that these are small, fast redistributions of separated charge, typical of K-changes in natural lightning (Ogawa, 1964). Figure 4a shows both the effect of the rocket firing in the nearby field mill and the correlated E-field change meter. As the rocket deploys the wire (A), the E-field change meter shows a distrubance typical of leader propagation (Uman, 1969) before the first discontinuity (B). The second discontinuity is also likely a K-change process. The smaller amplitude discharge and barely detectable leader structure is evident of the K-change occurring farther away from the sensor than the first. The thunder microphone positively identified the rocket launch on the printout.

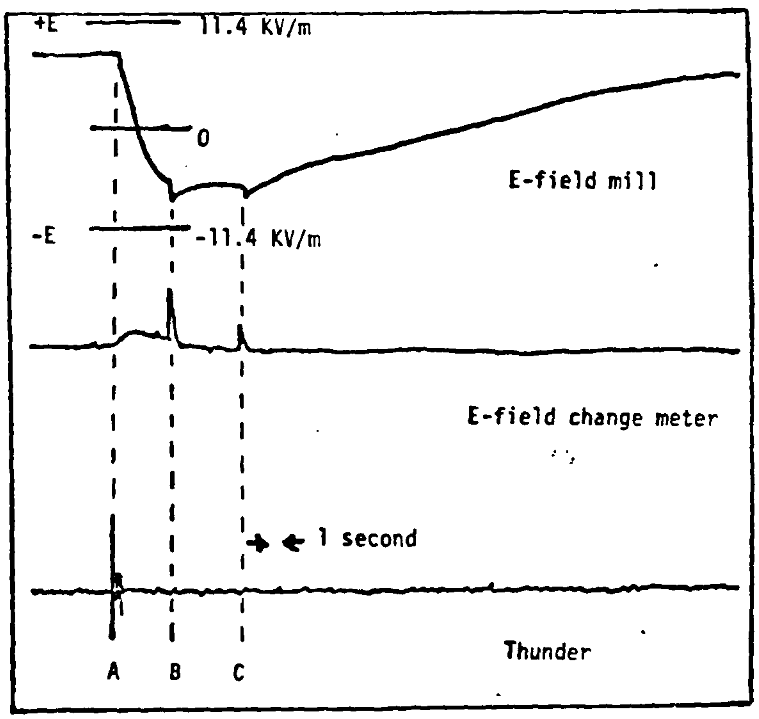


Figure 4a: E-field from KIVA mill, E-field change record, and thundermike output for 1st ENTAC firing (time increases from left to right)

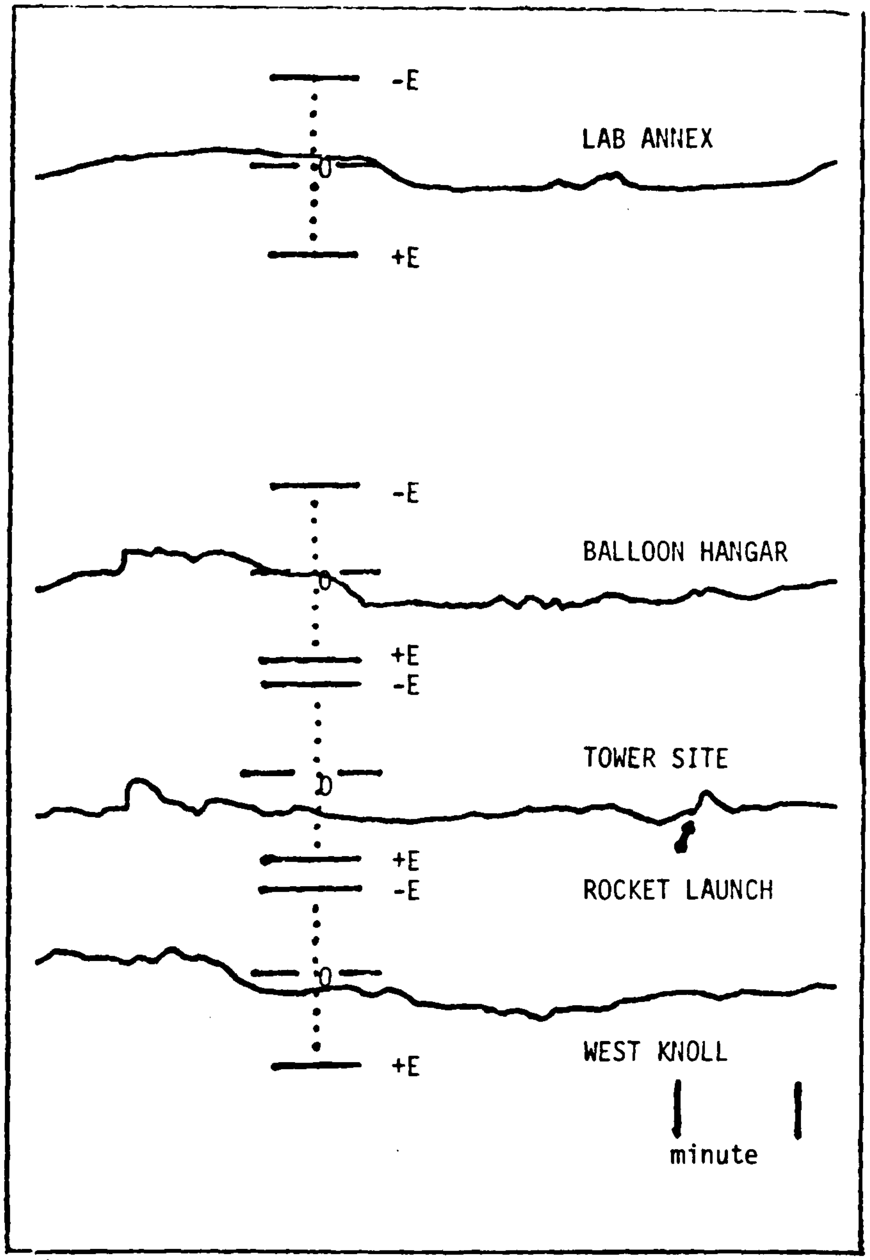


Figure 4b: Field mill records for 1st ENTAC firing: $\pm$ 15 KV/m full scale (time increases from left to right)

These field records can be correlated with the triggering rocket trajectory. Initially, the rocket deployed the wire near vertically for approximately four seconds before tipping over to travel horizontally westward. After several more seconds, the rocket curved toward the ground and eventual impact. The elevation of the grounded wire to about 300 meters altitude, although much slower than a leader, affected the field as would a leader. This is presumed to have triggered the K-change at some higher altitude. Later, as the rocket traveled west, a new charge volume would be accessible for possibly triggering the second K-change in a similar manner.

The remainder of the field mill network (Figure 4b) shows little influence from this launch, the Tower Site reflected only a 3 KV/m change while the Balloon Hangar showed approximately 1.5 KV/m, and no noticable effect was present at the further stations. This all suggests a small charge distributed on the wire, only affecting the nearby local area. The BIOMATIONs recording the CT, B dot and D dot data did not trigger on this attempt.

The field records for the second rocket (and successful trigger) are shown in Figures 5a, 5b, and 5c. The rocket was fired at a stable KIVA E-field of 12.3 KV/m, reducing the gradient to 1.4 KV/m before the high current return stroke is evident, jumping the E-field to -14.6 KV/m for a total change of 26.9 KV/m during the flash. The thundermike shows a 2.45 second delay from rocket launch to subsequent triggered discharge and is consistent with the field change. During this time span, the rocket would have reached an altitude of approximately 200 meters. The trace with expanded time frame indicates a subsequent stroke beginning

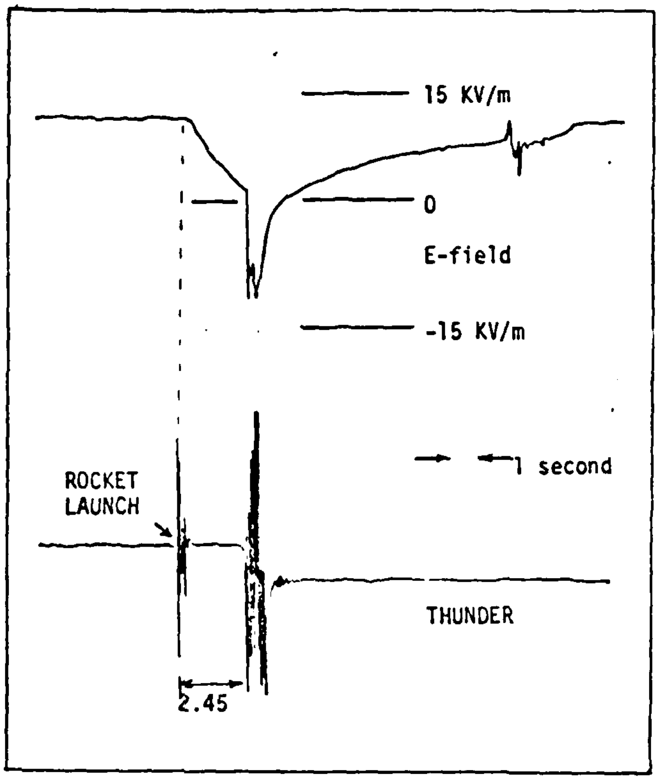


Figure 5a: Thunder vs KIVA E-field for triggered lightning discharge (time increases left to right)

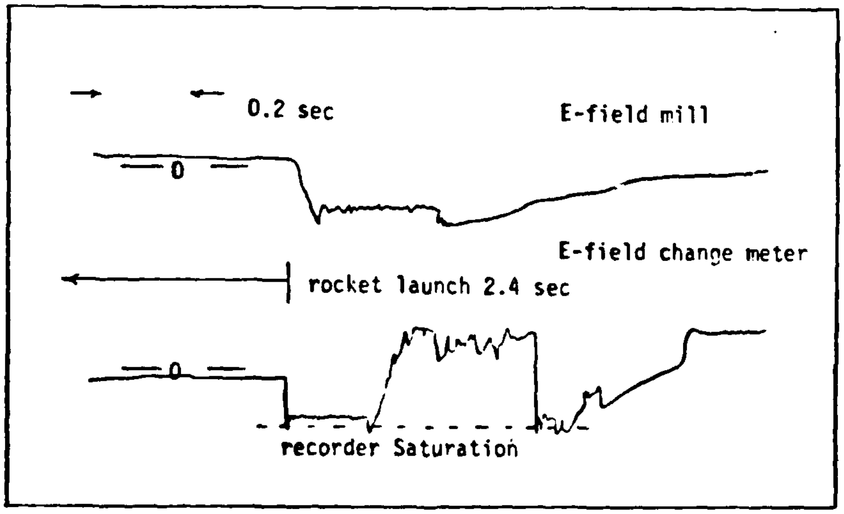


Figure 5b: Expanded Time Scale of KIVA E-field and E-field Change Meter for Triggered Discharge

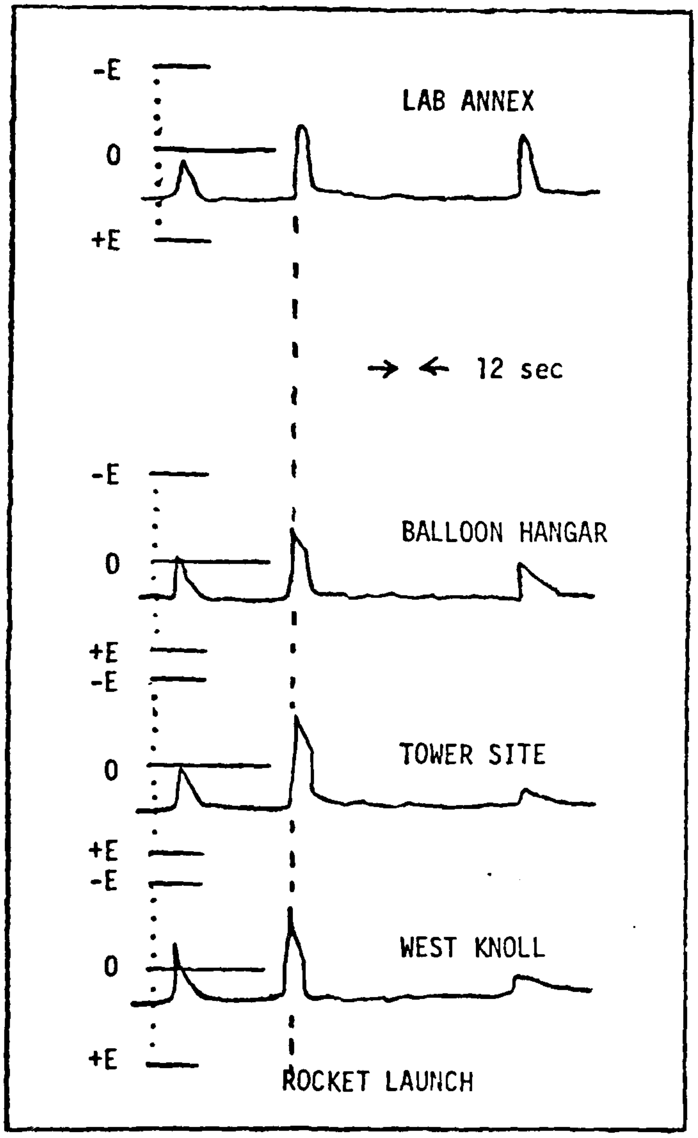


Figure 5c: Remainder of Field Mill Network Records for Triggered Discharge: $\pm$ 15 KV/m full scale

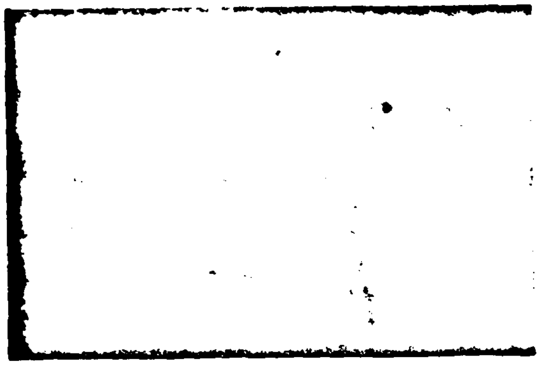
320 msec after the first return stroke (assuming none occurred during the first 190 msec when the recorder was in saturation). This result is in disagreement with the average time between subsequent strokes in natural lightning of about 100 msec (Uman, 1969). However, the persistance of the ionized metal wire channel could explain the time deviation between the first return stroke and the subsequent stroke(s). The remainder of the field mill network displayed a decreasing strength trend with distance from the trigger site as follows:

Tower Site	8 to -10 KV/m
Balloon Hangar	6.5 to -6 KV/m
West Knoll	6.5 to -8 KV/m
Lab Annex	7.5 to -6 KV/m

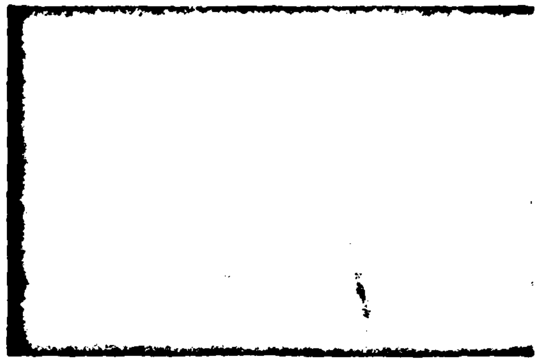
The third and fourth rockets were fired at random since the E-field readout instrumentation had previously malfunctioned. Playback revealed these rockets were fired at field values of 4 and 5.4 KV/m respectively without further incident.

Optical Measurement

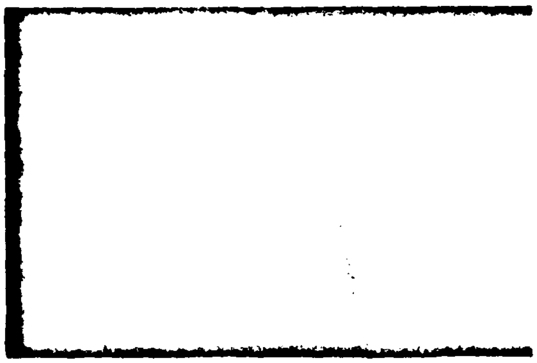
Video tape recorded the triggered lightning flash from the second rocket and clearly shows the ionized wire and upper arc channel with two upward going branches. A photo sequence of the video tape frames are presented in Figures 6a, 6b, and 6c. The pictures show the lightning arc channel merging with the wire at an approximate altitude of 200 m and following it to ground. The upward branching begins to separate at 350 m elevation. Although the ionized metal wire remains luminous, the upper branches eventually flicker and extinguish before a restrike



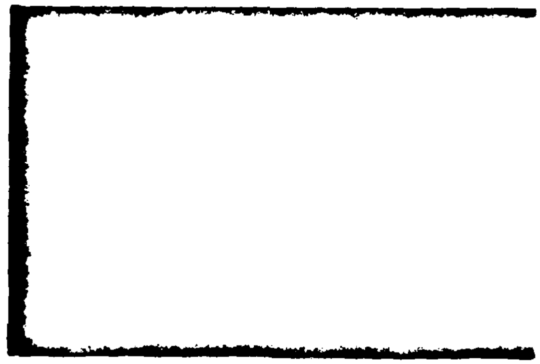
t = 0



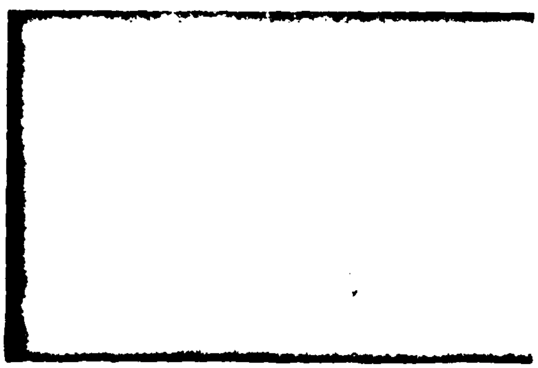
t = .04



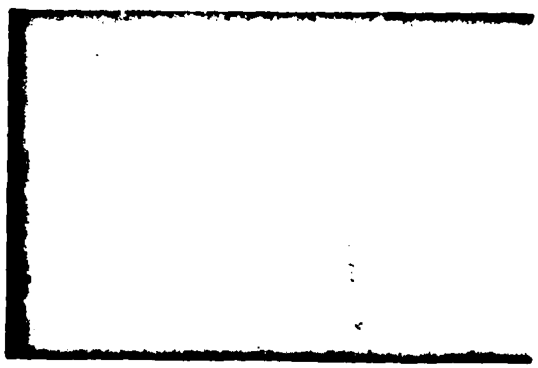
t = .08



t = .13



t = .17



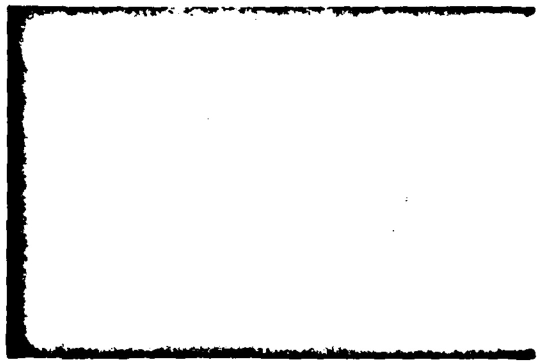
t = .21

Figure 6a: Sequence of Triggered Discharge from time t = 0 to t = .21

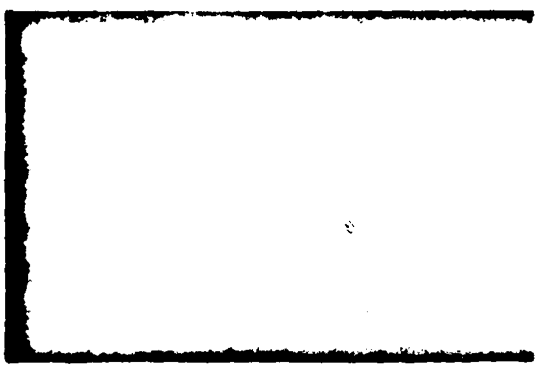
t = .25

t = .29

t = .33



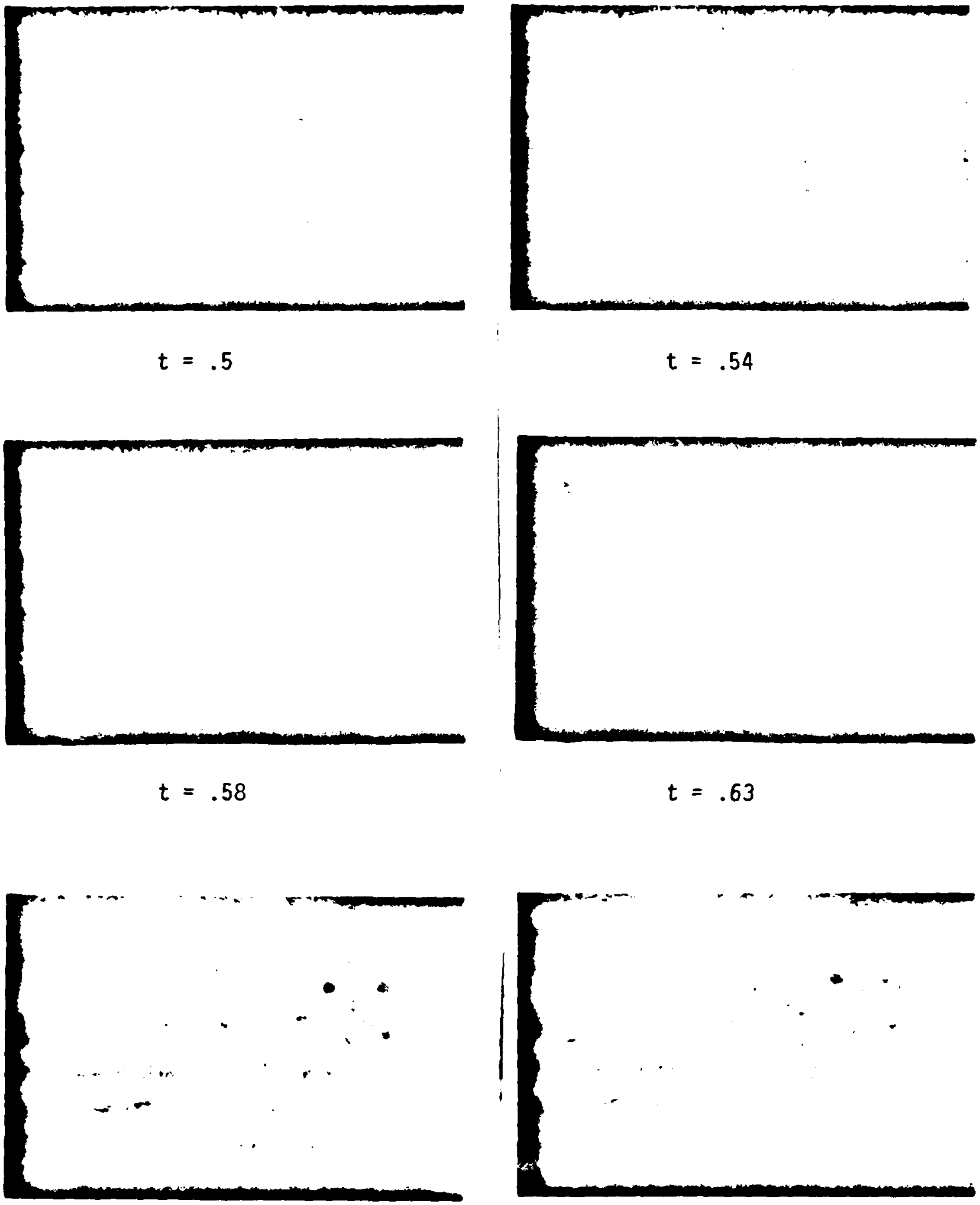
t = .38



t = .47

t = .46

Figure 6b: Sequence of Triggered Discharge from time t = .25 to t = .46



t = .5 t = .54

t = .58 t = .63

t = .67 t = .71

Figure 6c: Sequence of Triggered Discharge from time t = .5 to t = .71

reilluminates and alternates between the previously established paths. The approximate time of these restrikes can be correlated to the fast field changes to within the exposure time of the photo sequence ($\pm$ 21 msec). The total flash existed for 0.7 seconds. These photos are also used to establish and verify geometric restrictions and solutions to model calculations that will be performed later in this thesis.

V. ANALYSIS

With results being outlined in the previous chapter, a more thorough analysis is performed in this section. Computer simulations and error evaluation techniques are utilized to determine the location of the charge centers for the triggering attempts. The analysis is then compared to similar analyses for natural lightning.

Single Point Charge Model

Two of the more significant types of data collected are the sequenced photographs and the field mill records from the different stations atop the mountain site. The output from the five (5) field mills will result in a one degree of freedom system. This provides one more measurement reading than unknown variables in the equations for determining the location of the charge that was neutralized during the lightning flash. The location, thus determined analytically, can be correlated to the photographs to see if a satisfactory solution has been found or if further refinement needs to be performed. Although the photos show restrikes through alternating channel branches, the field mills do not have a frequency response fast enough to show the individual restrikes, therefore, the total flash is considered in the following discussion.

Assuming a spherically symmetric or point charge (Q), the electric field intensity (E) is given by:

$$E = Qa_r/4\pi\varepsilon_o r^2 \qquad \text{volts/m} \qquad (1)$$

where r is the distance from the charge in meters, ε_o is the permittivity of free space, and a_r is a unit vector in the r direction. If this charge is a distance (H) above a flat conducting plane the method of electrical images can be used to replace the "ground" plane with an image charge (-Q) resulting in the magnitude of the E-field from each charge as a function of distance (D) horizontally on the "ground" plane:

$$E = Q/4\pi\varepsilon_o(H^2+D^2) \quad (2)$$

However, since these vectors are pointing differently, vector additions of their components via the relations $\sin\Theta = H/(H^2+D^2)^{.5}$, and $\cos\Theta = D/(H^2+D^2)^{.5}$ yield:

$$E\ total = 2QH/4\pi\varepsilon_o(H^2+D^2)^{1.5} \quad (3)$$

pointed vertically as the horizontal components cancel.

To analyze the triggered discharge, the ground point termination is chosen as the origin of a rectangular coordinate frame. Although the photos showing two branchings within 500 m from one of the field mills suggest violation of the single point charge model, this is the simplest first order analysis and will show where further refinements are necessary. In line with the aforementioned assumption, the change in the E-field at each of the 5 stations is related to the change in charge by

$$\Delta E = \Delta Q z_o/2\pi\varepsilon_o[(x_o-x_i)^2+(y_o-y_i)^2+(z_o-z_i)^2]^{1.5} \quad (4)$$

where x_o, y_o and z_o are the charge initial location and x_i, y_i and z_i are the field mill coordinates. The charge parameters are determined by a least square fitting technique that minimized the total error from measured and calculated E-fields from 5 equations. The 4 unknowns can be estimated from the minimization of the chi-square function

$$X = \sum_{i=1}^{n} (EM_i - EC_i)^2/\sigma_i^2 \qquad (5)$$

where:

EM_i = measured E-field change at station i;

EC_i = calculation E-field change at station i;

n = number of stations

σ_i = standard error

This technique has been successfully used to determine charge center locations when the field mill locations are spread 5 or more kilometers such as the Kennedy Space Center network or St. Privat (Jacobson, 1976; LaRoche, 1980). The Langmuir Laboratory network, covering only 2 Km, does not have the precision of the larger networks. In addition the close proximity of the mills to the lightning discharge requires close scrutiny of any solution for possible violation of the assumptions. Equations (4) and (5) were implemented in computer simulations to determine the most likely parameters of the charge(s) neutralized by the triggered lightning flash. A copy of the computer program with a sample run is in Appendix A. The single point charge model did not yield an absolute minimum in the error function, but was asymptotically approaching a bound in the minimum error. Considering the programing steps of 100 m

increments and the insensitivity of the error function, a solution was chosen when the change of error between steps was less than two percent. The results of this simulation were a charge of approximately 10 coulombs at coordinates (2300, -1300, 3200) meters with an absolute error of about 50 volts/m. From both the scale of the error and the coordinates, which are a different direction than the video pictured channels, a single point charge model appears unsatisfactory.

Two-Charge Model

To improve results, the next step was to incorporate a two-charge model such that now

$$ECi = \frac{Q_1 H_1}{2\pi\varepsilon_o (H_1{}^2 + D_1{}^2)^{1.5}} + \frac{Q_2 H_2}{2\pi\varepsilon_o (H_2{}^2 + D_2{}^2)^{1.5}} \quad (6)$$

In addition to the increased complexity of the simulation there is no guarantee that solutions are unique. In order to overcome some of these difficulties, bounds were placed on some parameters in accordance with photo correlation. As the arc channel was visible to 500 m and branches at approximately 350 m, solutions with a z_o lower than 350 m were discounted. It was also assumed that the charge centers should each be allocated to one of the two visible branches of the discharge. Previous pictures of rocket-triggered lightning (Fieux, 1978; Boulay, 1979) have shown reasonably straight, albeit flared, branched structure which suggests an additional restrictive assumption. The charge centers are therefore assumed to be contained somewhere within a 15 degree half-angle cone emanating from the visible branching centered on the branches directional

axis. The computer simulation extended beyond these bounds to discover and evaluate trends, but solutions beyond these limits must be viewed cautiously. The solution with best fit (least error) and still within the above limits is a Q_1 of about 12 coulombs with initial coordinates (-500, 1500, 7250) meters (13° off conical axis) and a Q_2 of 0.1 coulombs at (200, 250, 450) meters (15° off conical axis). The total error for these parameters was estimated to be less than 6.5 V/m.

The error is usually considered acceptable if it is on the order of the degree of freedom of the system for nearby storms (Jacobson, 1976). However, that criterion was obtained using the Kennedy Space Center field mill network spaced over 10 Km and yielding charge locations to within 0.5 Km in x, y, and z. For the Mt. Baldy situation, error sources degrading the solution can be seen by recalling that the Langmuir Lab field mills are within a 2 Km spread, and the following assumptions were made:

a. the conducting plane is flat in this mountain environment;
b. a point charge model is valid in the close proximity of the KIVA field mill;
c. the corona space charge is being ignored.

Since the computed error was approaching acceptability, an error sensitivity analysis was performed. As expected the major error component was introduced via the KIVA field mill equations.

The optimum parameters were recomputed with the KIVA location shifted in the simulation by 50 m in $\pm$ x, $\pm$ y, and $\pm$ z. The optimum location remained the same but the error ranged from an increase of 10% -70% in $\pm$ x, $\pm$ z, and - y and actually decreased 20% for a shift in + y. It should

be noted here that the lightning's actual point of ground contact was 15 m in + y from the KIVA mill. Eliminating the KIVA mill entirely from the computations reduced the minimum error to approximately 3.6 V/m. This demonstrates that over half of all the calculated error resulted from the KIVA field mill, and therefore the KIVA data inputs should be neglected in this charge location analysis. The instrumentation measurement error is also a strong factor in the error sensitivity. If the 5% measurement error is increased to an assumed 6% while still retaining the KIVA mill, the chi-square error function is reduced by 35% to an absolute error of 3.7 V/m. This analysis shows that the two charge model is as reasonable an estimate as possible for this instance; any solution from a three-charge model would lose all significance in variable error. To increase precision, in the future, additional field mills over a larger area need to be installed.

Summarizing, this chapter has estimated the charge neutralized by the triggered flash to have a main center of 12 coulombs located 500 m south, 1500 m west, 7250 m above the rocket launcher and a smaller charge volume of 0.1 coulomb within 500 m of the launcher. These determinations, limited by the equipment and data available, are not likely to be the precise solution, but on first order analysis are comparable to analysis of natural lightning charge locations.

Charge on Wire

As the rocket/wire gained altitude, the KIVA field mill displayed a large decrease of the statice E-field before the sharp discontinuities denoted a discharge. Until the fast discharge, the change in the static E-field is due to a charge of opposite polarity distributed on the grounded

wire negating some of the E-field from the charged thunderclouds. To obtain the value of this charge it is assumed that its entirety is concentrated in a point at the tip of the rocket as it advances into the field gradient. In reality some of the charge is likely to be distributed along the length of the wire according to current models (Bruce-Golde, 1941; Lin, 1980). However, the point charge assumption would result in the largest value or upper bound of the charge. The position of the rocket at the time of return stroke initiation can be determined by photo triangulations and velocity schedule of the rocket. With these parameters known, the charge can be determined via equation (4).

For the first ENTAC firing, approximately .07 coulombs is calculated as the upper bound for charge on the wire. The second firing resulted in only .029 coulombs before the triggered discharge. These values were tested in the computer simulations for charge center location without affect. Extending the values to discover trends showed that a charge of less than .1 coulomb had no effect on computer results for this specific example.

VI. ROCKET TRIGGERED LIGHTNING TEST STATION

An important goal of this thesis is the establishment of a rocket-triggered lightning test technique for Research and Development purposes. The developed techniques are then applied to specific tasks of the Air Force Wright Aeronautical Laboratories (AFWAL/FIESL), who sponsored this work. The intent of the FIESL office is to expose a representative aerospace vehicle structure and sub-components to a full scale lightning strike at the earliest feasible opportunity. This chapter incorporates the information from the previous sections to progress toward the FIESL goal. In this respect, the following recommendations are tempered using existing hardware and preestablished basic facilities. Since budgetary constraints often prevent total implementation of new hardware, a knowledge of the resulting impact on the quality and quantity of the test data is imperative for a compromise decision making process.

Site Location

There are several parameters which must be considered when choosing a potential site location for a lightning triggering rocket system. First, there should be a predictably high occurrence of storms directly overhead or nearby during the average thunderstorm season to achieve economic utilization of the system. The immediate area should be relatively flat to prevent perturbations in the ground plane and thereby complicate field calculations. For safety, restricted airspace, or at least a controlled area will be required for the rocket launches. If full scale vehicle

susceptibility testing is eventually to be accomplished, towing or taxiing proximity to an airfield is an important consideration. Several places within the United States fulfill these requirements, most notably MacDill AFB, near Tampa, Florida and Kennedy Space Center (KSC), Cape Canaveral, Florida. Isokeraunic maps show the nation's most frequent storms occur in the Tampa area, with 90 storm days per year. KSC also has high storm activity with 70-80 days a year. With respect to KSC, a field mill array network already exist, as this site was used for the Thunderstorm Research International Program (TRIP) (Pierce, 1976). A position near the Orbitor Landing Field would be a choice location for establishing a triggering station. Unfortunately, an additional AFWAL obstacle is the short timespan to achieve payoff from this project and it is unlikely that the KSC Space Shuttle priorities would permit establishment of such a triggering station before the 1982-83 time period. Necessary facility build-up at Mac Dill would be likewise time prohibited and costly. In the interest of expediency a compromise site could be chosen at Langmuir Lab, Mt. Baldy, New Mexico, which normally experiences 50-60 storms during the summer season. Although in mountainous terrain, the various equipment/sensors are deployed along a 2 Km ridge with approximately 120 m variation in elevation. The airspace over the mountain in already restricted for the purpose of firing rockets. In addition, here the basic facilities exist, can be easily augmented, and although full size planes cannot be flown in, at least component and subsystem testing can be performed within the upcoming storm season.

Optical Measurement

Optical instrumentation is required with duplicated field of views (FOV) with different exposure times for thorough optical analysis. Two orthogonal wide angle FOV video tape recording cameras would determine actual location of lightning arc channels and branches. Standard commercial video equipment of 60 frames/sec (8.3 msec exposure per frame) has been shown to be adequate for lightning research (Brantley, 1975; Winn, 1973). Suggested locations for deployment are the Lab annex building and the telemetry station near Blue Cut. In these positions, the cameras data can be augmented by existing "all sky" cameras at South Baldy Peak and the Balloon Hangar. A high speed Fastax 16 mm (1000 f/s) camera at one of these same FOV would show sub-millisecond changes in branching, restrikes, and dart leaders documenting the triggered flash in more detail. A Boys or Fastax "streak" camera is required to denote the submillisecond structure of leader and return stroke luminosity processes (Uman, 1969). The French researchers at St. Privat d'Allier have developed a came for determing the velocity of the return stroke (Hubert, 1980), and such a device would potentially yield information about the severity of the threat contributed by the different phases of a lightning flash. Although not mandatory for AFWAL testing purposes, optical spectroscopy of the triggered flash is of interest to show the energy frequency content (Orville, 1975).

Electromagnetic Measurements

The presently existing five field mill network atop Mt. Baldy should be augmented by at least one more mill located 500 m or more east or west of the triggering site. This will permit neglecting the errors introduced by the KIVA mill adjacent to a discharge and still have a one degree of freedom system for calculating a single charge center location. This deployment would also increase the network's east-west precision. A logical position is the previously mentioned telemetry station near Blue Cut. If two charge centers are to be determined uniquely at least eight field mill stations are required. This size network is desirable but available site power may prevent this option for the upcoming season. Due to the low frequency response of the field mills (120 Hz), strip chart recorders are sufficient for this data. To determine the different events in a flash, a fast E-field antenna should be coupled to a magnetic tape recorder of comparable frequency response (Kitagawa, 1960; Fisher, 1972; Krider, 1977). For very detailed examination of a discharge's initial peak and risetime, a high frequency response model of the EG&G ACD-6 D-dot sensor (Asymptotic Conical Dipole) and two perpendicular B-dot sensors, EG&G MGL-4 (Multi-Gap Loop) will characterize the fields with 350 MHz or better (EG&G, 1980). These sensors should be located within 500 m of the trigger site. Recording this data requires transient analyzers/digitizers such as the BIOMATION 8100 or Tekronix 7912. Unfortunately, at the fast sampling rate required for this frequency response, the fixed memory size limits the usable data window. For example, the BIOMATION could only observe a 20 microsecond window at this sample frequency (20 nsec/sample).

One of the more important measurements of a triggered lightning discharge is the current in the stroke. This can be accomplished using a Pierson Model 301X current transformer around the electrode to ground or just as satisfactorily with a current shunt off of the grounding electrode. An additional method is to detect the induction B field in a coil and compute the causing current. French scientist have used this device with good results (Fieux, 1978). Any measurements made in direct vicinity of the triggered discharge need to be transmitted to their respective recorders via fibre optic cable to allow a wide band width and to eliminate flashover effects from a nearby flash interfering with the signals from the sensors.

Test Structure

Figures 7 and 8 show the aluminum test cylinder (a representative aerospace vehicle fuselage) which the AFWAL desires to subject to a triggered-lightning discharge and a proposed configuration for this test (Schubert, 1981). Although this set-up will likely result in a triggered discharge directly attaching to the cylinder, minor alterations will reduce the chance for experimental mishap, reduce introduction of potential error and increase data output.

Directly attaching the wire-bottle support to the test cylinder and wiring the bottom of the cylinder to the current shunt ground path increases the chance of all the discharge current taking the desired path through the test structure. Standoff distance between the pre-loaded wire/rocket reduces the chance of a stray arc-over which would produce a subsequent

failure or changeover delay. The thin connecting wire would quickly vaporize and establish an arc to the grounding shunt. The specimen support arrangement can be reconfigured, shortening the support poles and thereby reducing the chance of lightning tracking down the wet poles. The shortened poles would also shorten crank down and reload time for a possibly increased launch rate during a given storm. Regardless of final configuration, an open shutter or streak camera should be aimed at the cylinder to identify any current tracking. A modified test configuration is shown in Figure 9.

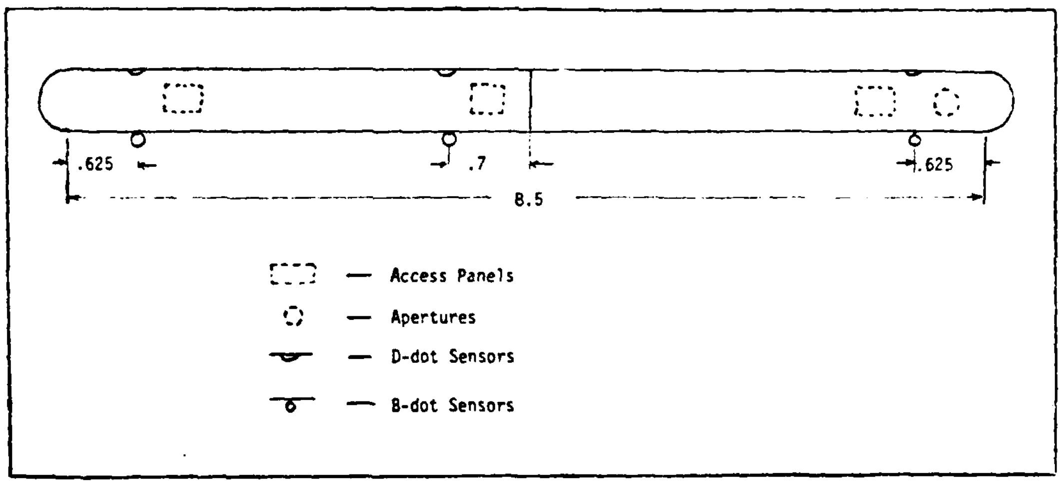


Figure 7: Diagram of Rocket-Triggered Lightning Test Cylinder. All dimensions are shown in meters.

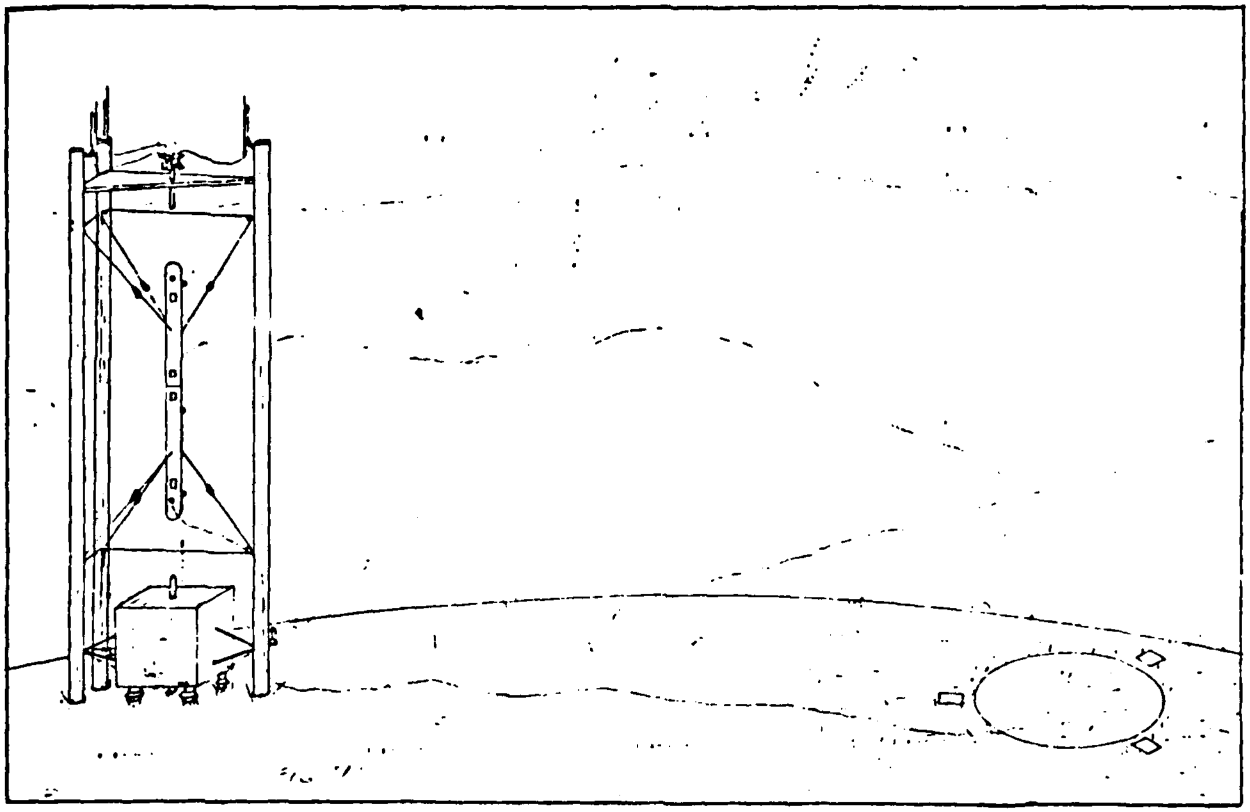


Figure 8: Diagram of triggered-lightning test configuration

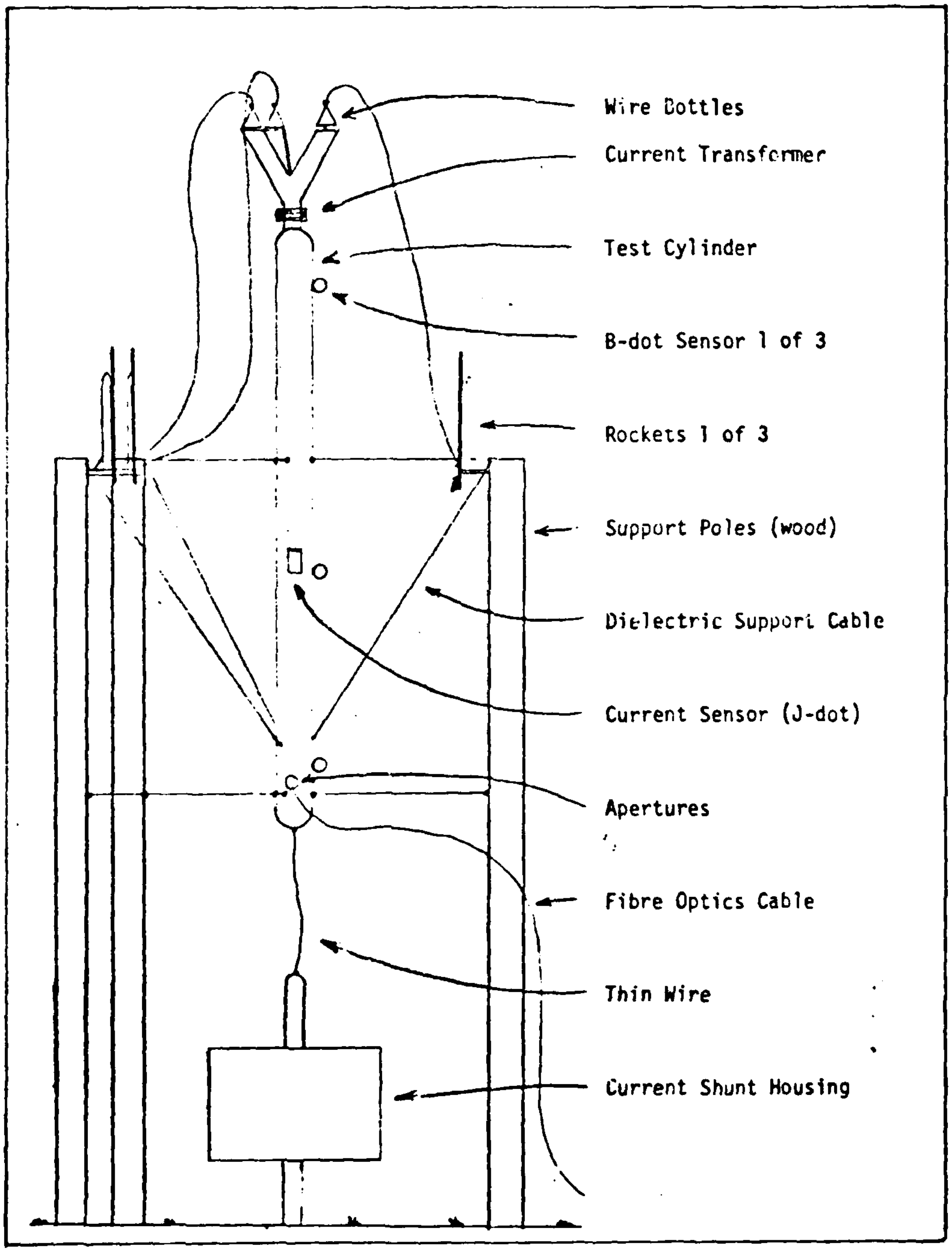


Figure 9: Diagram of proposed triggered-lightning test configuration

The test cylinder requires additional special instrumentation equipment to positively identify the resultant lightning effects. A Pierson Model 301X (50 KA, 100 MHz) current transformer around the top hard attachment point would yield the current waveform incident upon the specimen and should correlate with the current shunt at the ground termination. A EG&G MGL-S4 J-dot skin current sensor (230 MHz response) would yield the current density which contributes to electromagnetic field internal to the structure and can also be used to compute the current waveform given the following assumption: the aluminum cylinder is a near perfect conductor and the frequency content of the current waveform is high enough so that the cylinder's electrical skin depth is virtually zero resulting in only a surface current; also the current is assumed uniformly distributed along the cylinder circumference. From Faraday's Law, the sensor output in volts becomes (EG&G 1107, 1980)

$$V = \mu_o A \frac{dJ_s}{dt} \sin\theta \qquad (7)$$

where: μ_o = permeability of free space

A = sensor equivalent area (M^2)

J_s = surface current density (Amps/M^2)

θ = angle between sensor axis and J_s vector

Aligning the sensor in the longitudinal axis of the cylinder and integrating its output would result in a waveform that is a constant times the cross section ratio (cylinder circumference/sensor width) factor different from the incident current waveform assuming the dynamic range of the recorders preserves the low frequency components. Another current correlating method

is to mount EG&G CML-7 B-dot sensors aligned laterally along thc exterior of the specimen. These sensors detect magnetic field from a current according to (EG&G 1106, 1980)

$$V = \overline{A} \cdot \frac{d\overline{B}}{dt} \qquad (8)$$

where: V = volts

$\overline{B}$ = the magnetic flux density vector (in teslas)

$\overline{A}$ = equivalent area vector

Again integration of the output results in a waveform that varies by a constant factor varience from the incident magnetic field. Two or more of these distributed along the length of this test cylinder would detect resonances if the outputs are synchronously recorded on a 100 MHz device (Hewlett-Packard 100 MHz dual beam storage oscilloscope or equivalent). Since these sensors only respond to B resulting from a current, installation of D-dot sensors (EG&G FPD-1 or FPD-2) would yield the total electric field. The different field readings can be correlated to learn about the different phases of the RLT process. A significant advantage with this test technique is the capability to install active circuitry (i.e. digital avonics or guidance control) inside the test cylinder and monitor its function for upset during the prestrike streamering and high current phases of the strike. All data signals measured on the cylinder need to be transmitted via fiber optic cable to maintain electrical isolation and to prevent the lightning from affecting the transmission line directly. The fiber optic data channels also need comparable bandwidth to its respective recorders so as not to inadvertently filter the data signals.

As previously mentioned the limited windows for this fast data result in only the beginning of the flash, the first major peak, being fully expanded. The entire flash will only have a millisecond resolution from analog instrumentation. A possible solution for this problem is to augment the transient digitizers with expanded memory (Pitts, 1981) and add computer processing. With all recording devices, their power and grounding systems require protection against the nearby lightning from causing interference with records and losing data.

Operation

In preparation for a storm, three rockets and wire bottles would be readied on the test cylinder and supports. The field mill at the KIVA (50 m from launch site) would be the indicator for firing opportunity. A good chance for triggering exist when 9 KV/m is exceeded. One rocket is launched with the others' firing circuit electrically "safed". As soon as the triggered discharge data is transferred to "permanent" storage, another launch sequence may commence (the bottom connecting wire may or may not be replaced). If a launch did not result in a trigger down the wire, further launches must be postponed until the spent wire is removed from the test structure and immediate area.

VII. CONCLUSIONS AND RECOMMENDATIONS

The following discussions are primarily based on the experiments performed for this thesis in the 1980 season and participatory observations during experiments of the previous 1979 season. However, the author's prior work in associated areas, (Lippert, 1978), has contributed to the recommendations in this section.

Conclusions

1. This effort has shown that the ENTAC rocket/wire system can be successful in triggering lightning atop Mt. Baldy Peak, New Mexico. Analysis estimated that this triggered flash neutralized at least two charge centers of approximately 12 coulombs and 0.1 coulombs respectively.

2. The subsequent stroke activity associated with this triggered discharge did not occur until 300 msec after the initial return stroke had been established. This duration is three times longer than that of typical natural lightning and is likely a result of the ionized wire.

3. A rocket/wire elevated to a couple hundred meters is capable of "triggering" intracloud lightning at higher altitudes. It appears that this process can produce charge redistributions at field strength levels slightly below the baseline threshold of 9 KV/m for triggered cloud-to-ground discharge. Although, no visible or audible evidence of intracloud lightning was present, the field readings from this isolated example suggest a triggered intracloud lightning strike may be possible.

4. From review of existing information, the capabilities offered

through the use of RTL is just as appropriate for hardware testing as the use of presently available simulators/generators. Some evidence, discussed in Chapter II, suggests that triggered lightning may be the actual threat of direct strikes to aerospace vehicles rather than naturally occurring lightning strikes.

5. From these reported experiments in conjunction with similar ones, (Standler, 1977; Fieux, 1978; Newman, 1964), it appears that a successful rocket lightning-triggering system does not depend on a particular type rocket. The common parameter of the varied triggering rockets' performance appears to be the introduction of a conductor across the resultant electric field faster than the corona current and space charge redistribution can counteract the wires effect.

6. Another important factor in successful triggers has been the existence of a local E-field on the order of 9 KV/m or better. The Pierce criterion mentioned in Chapter II, that approximately a megavolt of static field potential is required to be "shorted" by a conductor to result in a trigger is neither verified nor disproved and remains a reasonable first order estimate.

7. This work substantiates the theory that field mills in direct proximity of a lightning flash (50 m) should not be used for charge location analysis via symetrical/point charge model. Indications are that field mills as close as 400 m, while they will increase the error inherent in the analysis, can be used to determine approximate charge locations using this technique.

8. If measurements close to the lightning's arc channel or ground contact point are to be attempted, thorough flashover protection measures are required. This concerns direct flashover to instrumentation, induced

signals in transmission wires, and impulse transients in the reference ground around the site.

9. In summation, the principle of rocket-triggered lightning is feasible for a research and development test technique for subjecting Air Force systems to full scale lightning threats.

Recommendations

This thesis started by reviewing previous work in the area of triggered lightning. The purpose of those experiments was to develop a triggering capability and investigate the processes and phenomenology of natural and triggered lightning. In this work experiments were conducted to identify important factors and components of a useful rock triggered lightning system as well as potential problems which need he olved. The results of this effort were then applied to a proposal of an immediately useable test technique configuration for full scale lightning testing of specific Air Force aerospace vehicle subsystem hardware. With regard for the aforementioned accomplishments, further work is recommended in the following areas:

a. Further refinement of the proposed test configuration is desired, primarily concerning improved data acquisition. This is mainly a hardware limitation requiring more channels of simultaneous, time correlated, faster response over longer window measurements. Micorprocessors and new software could help in solving this problem.

b. Action should be pursued towards eventual development of a

triggering station at a site where operational aircraft may be flown in for testing. Kennedy Space Center is such a potential site.

c. Investigation should be continued into alternative methods of triggering lightning. Triggering by lasers is a possible candidate (Schubert, 1978).

d. Efforts should be continued in development of generators and simulators which can replicate at least part of the lightning threat to aerospace vehicles without dependence upon naturally occurring thunderstorms.

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APPENDIX

CHARGE MODEL ANALYSIS COMPUTER SIMULATION

The computer program for the single charge model is a simple four nested loop iterating possible values for the four unknowns of equation (4). On each iteration, the least squares error criterion is applied to the calculated and measured field strengths. The parameters which result in the minimum error is retained as a solution.

The two charge model uses the same technique, but the fields are now computed via equation (6). For this model to describe the parameters, eight nested loops are required making an exhaustive search routine, time consuming and expensive. To reduce computing time, loop advances were utilized to increment parameters after the local minimum had been obtained.

```
      PROGRAM TWOCRG (INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
      DIMENSION  EM(5), SIG(5), ED(5) ,  ED2(5)   , BUMPS(50),BUMPS(50)
      REAL MIN
      EM(1)=26900.
      EM(2)=18000.
      EM(3)=12500.
      EM(4)=13500.
      EM(5)=11500.
      L=1
      DO 50 L=1,5
      SIG(L)=(450.+((.05*EM(L))**2))
   50 CONTINUE
      WRITE(6,10)
      AMIN=9000000.
      Y2=250.
      DO 320 N4=1,5
      X2=200.
      DO 310 N3=1,6
      X1=-200.
      DO 300 N2=1,5
      Y1=400.
      DO 300 N=1,6
      D=3.5
      DO 710 M=1,6
      DO 45 L=1,43
      BUMPS(L)=9000000.
   45 CONTINUE
      MIN=9000000.
      D2=.1
      DO 500 J=1,24
      Z1=11500.
      DO 55 L=1,43
      BUMPS(L)=9000000.
   55 CONTINUE
      DO 500 L=1,41
      Z=Z1
      X=X1
      Y=Y1
      ST=(((X+375.)**2)+((Y-160.)**2)+((Z+51.)**2))**1.5
      BH=(((X+900.)**2)+((Y-500.)**2)+((Z+51.)**2))**1.5
      WK=(((X+1400.)**2)+((Y-575.)**2)+((Z+120.)**2))**1.5
      AX=(((X+1700.)**2)+((Y+650.)**2)+((Z+49.)**2))**1.5
      Y=Y+15.
      ED(1)=D*Z/(((X*X)+(Y*Y)+(Z*Z))**1.5)
      Y=Y-15.
      ED(2)=D*Z/ST
      ED(3)=D*Z/ BH
      ED(4)=D*Z/WK
      ED(5)=D*Z/AX
      Z=250.
      X=X2
      Y=Y2
      DUM=9000000.
      DO 400 K=1,41
      ST=(((X+375.)**2)+((Y-160.)**2)+((Z+51.)**2))**1.5
      BH=(((X+900.)**2)+((Y-500.)**2)+((Z+51.)**2))**1.5
      WK=(((X+1400.)**2)+((Y-575.)**2)+((Z+120.)**2))**1.5
```

```
      AX=((((X+1750.)**2)+((Y+650.)**2)+((Z+49.)**2))**1.5
      Y=Y+15.
      EC2(1)=56.6E9*(EC(1)+(Q2*Z/(((X*X)+(Y*Y)+(Z*Z))**1.5)))
      Y=Y-15.
      EC2(2)=56.6E9*(EC(2)+(Q2*Z/ST))
      EC2(3)=56.6E9*(EC(3)+(Q2*Z/BH))
      EC2(4)=56.6E9*(EC(4)+(Q2*Z/WK))
      EC2(5)=56.6E9*(EC(5)+(Q2*Z/AX))
      I=1
      CHISQ=0.
      DO 200 I=1,5
      CHI=((EM(I)-EC2(I))**2.)/(SIG(I))
      CHISQ=CHISQ+CHI
  200 CONTINUE
      IF (CHISQ. GT. DUM) GO TO 499
      IF (CHISQ. GT. MIN) GO TO 65
      IF (CHISQ. GT. AMIN) GO TO 77
      AMIN=CHISQ
      AQ=Q
      AQ2=Q2
      AX1=X1
      AY1=Y1
      AZ1=Z1
      AX2=X2
      AY2=Y2
      AZ=Z
   77 MIN=CHISQ
      QM=Q
      Q2M=Q2
      X1M=X1
      Y1M=Y1
      Z1M=Z1
      XM=X
      YM=Y
      ZM=Z
   65 Z=Z+250.
      DUM=CHISQ
      BUMP5(L)=DUM
      BUMP6(J)=DUM
  400 CONTINUE
  499 Z=Z-250.
      DIF=BUMP5(L)-BUMP5(L-1)
      DUD=.2*DUM
      IF (DIF. LT. 15.) GO TO 88
      IF((BUMP5(L). GT. BUMP5(L-1)) .AND.(L. GT.5))GO TO 599
   88 Z1=Z1-250.
  500 CONTINUE
      DIF6=BUMP6(J)-BUMP6(J-1)
      IF (DIF6.LT.2 .) GO TO 599
      IF ((BUMP6(J).GT.BUMP6(J-1)).AND.(J.GT.5)) GO TO 601
  599 Q2=Q2+.5
  600 CONTINUE
  601 WRITE(5,18)QM,X1M,Y1M,Z1M,Q2M,XM,YM,ZM,MIN,AMIN
      Q=Q+3.
  700 CONTINUE
      Y1=Y1+300.
  800 CONTINUE
```

```
      X1=X1+100.
  910 CONTINUE
      X2=X2-100.
  910 CONTINUE
      Y2=Y2-200.
  920 CONTINUE
   10 FORMAT(2X,8F10.1,5X,2F12.3)
   1  FORMAT(9X,1HO,5X,2HX1,9X,2HY1,9X,2H71,9X,2HO2,10X,1HK,10X,1HY,10X,
     11H7,15X,3HMIN,5X,4HAMIN)
   2  FORMAT(5F10.1,3F10.0,2F10.3)
 1000 STOP
      END
```

CO REFERENCE MAP (R=1)

SN TYPE	RELOCATION				
REAL		4713	AO	REAL	
REAL		4705	AX	REAL	
REAL		4720	AX2	REAL	
REAL		4721	AY2	REAL	
REAL		4717	A71	REAL	
REAL		4752	BJMP5	REAL	ARRAY
REAL	ARRAY	4712	CHI	REAL	
REAL		4733	DIF	REAL	
REAL		4735	DJM	REAL	
REAL	ARRAY	4755	ED2	REAL	ARRAY
REAL	ARRAY	4710	I	INTEGER	
INTEGER		4707	K	INTEGER	
INTEGER		4673	M	INTEGER	
REAL		4671	N	INTEGER	
INTEGER		4655	N3	INTEGER	
INTEGER		4672	O	REAL	
REAL		4734	OUO	REAL	
REAL		4724	O2M	REAL	
REAL	ARRAY	4702	ST	REAL	
REAL		4700	X	REAL	
REAL		4655	X1	REAL	
REAL		4654	X2	REAL	
REAL		4731	YM	REAL	
REAL		4725	Y1M	REAL	
REAL		4677	7	REAL	
REAL		4675	71	REAL	
REAL					

MODE

2054 OUTPUT 0 TAPE5 2054 TAPE6

ELS

FMT	4572	18	FMT	4605	20	FMT	NO REF
	0	50		0	55		

PROGRAM LENGTH 12400 674
BUFFER LENGTH [illegible] 1972
520 00 CM USED

D	X1	Y1	Z1	Q2	X	Y	Z	MIN	AMIN
3.5	-200.0	400.0	3750.0	.1	200.0	250.0	500.0	29.828	29.828
6.5	-200.0	400.0	5250.0	.1	200.0	250.0	500.0	10.158	10.158
9.5	-200.0	400.0	6500.0	.1	200.0	250.0	500.0	8.835	8.835
12.5	-200.0	400.0	7500.0	.1	200.0	250.0	500.0	8.236	8.236
3.5	-200.0	700.0	3750.0	.1	200.0	250.0	500.0	23.150	8.236
6.5	-200.0	700.0	5250.0	.1	200.0	250.0	500.0	13.176	8.236
9.5	-200.0	700.0	6500.0	.1	200.0	250.0	500.0	8.946	8.236
12.5	-200.0	700.0	7500.0	.1	200.0	250.0	500.0	8.075	8.075
3.5	-200.0	1000.0	3500.0	.1	200.0	250.0	500.0	26.639	8.075
6.5	-200.0	1000.0	5250.0	.1	200.0	250.0	500.0	12.503	8.075
9.5	-200.0	1000.0	6250.0	.1	200.0	250.0	500.0	8.378	8.075
12.5	-200.0	1000.0	7250.0	.1	200.0	250.0	500.0	7.989	7.989
3.5	-200.0	1300.0	3500.0	.1	200.0	250.0	500.0	30.958	7.989
6.5	-200.0	1300.0	5000.0	.1	200.0	250.0	500.0	10.633	7.989
9.5	-200.0	1300.0	6250.0	.1	200.0	250.0	500.0	7.313	7.313
12.5	-200.0	1300.0	7250.0	.1	200.0	250.0	500.0	6.712	6.712
3.5	-200.0	1500.0	3250.0	.1	200.0	250.0	500.0	35.526	6.712
6.5	-200.0	1500.0	5000.0	.1	200.0	250.0	500.0	12.807	6.712
9.5	-200.0	1500.0	5250.0	.1	200.0	250.0	500.0	9.375	6.712
12.5	-200.0	1500.0	7250.0	.1	200.0	250.0	500.0	6.642	6.642
3.5	-200.0	1900.0	3000.0	.1	200.0	250.0	500.0	44.567	6.642
6.5	-200.0	1900.0	4750.0	.1	200.0	250.0	500.0	13.246	6.642
9.5	-200.0	1900.0	6000.0	.1	200.0	250.0	500.0	7.744	6.642
12.5	-200.0	1900.0	7000.0	.1	200.0	250.0	500.0	6.358	6.642
3.5	-100.0	400.0	3750.0	.1	200.0	250.0	500.0	23.936	6.642
6.5	-100.0	400.0	5250.0	.1	200.0	250.0	500.0	10.822	6.642
9.5	-100.0	400.0	6500.0	.1	200.0	250.0	500.0	9.319	6.642
12.5	-100.0	400.0	7500.0	.1	200.0	250.0	500.0	9.457	6.642
3.5	-100.0	700.0	3750.0	.1	200.0	250.0	500.0	27.951	6.642
6.5	-100.0	700.0	5250.0	.1	200.0	250.0	500.0	11.245	6.642
9.5	-100.0	700.0	6500.0	.1	200.0	250.0	500.0	9.536	6.642
12.5	-100.0	700.0	7500.0	.1	200.0	250.0	500.0	8.434	6.642
3.5	-100.0	1000.0	3500.0	.1	200.0	250.0	500.0	23.585	6.642
6.5	-100.0	1000.0	5000.0	.1	200.0	250.0	500.0	12.517	6.642
9.5	-100.0	1000.0	6250.0	.1	200.0	250.0	500.0	8.221	6.642
12.5	-100.0	1000.0	7250.0	.1	200.0	250.0	500.0	7.721	6.642
3.5	-100.0	1300.0	3500.0	.1	200.0	250.0	500.0	34.178	6.642
6.5	-100.0	1300.0	5000.0	.1	200.0	250.0	500.0	11.274	6.642
9.5	-100.0	1300.0	6250.0	.1	200.0	250.0	500.0	7.612	6.642
12.5	-100.0	1300.0	7250.0	.1	200.0	250.0	500.0	6.727	6.642
3.5	-100.0	1500.0	3250.0	.1	200.0	250.0	500.0	30.944	6.642
6.5	-100.0	1500.0	5000.0	.1	200.0	250.0	500.0	14.434	6.642
9.5	-100.0	1500.0	6250.0	.1	200.0	250.0	500.0	9.159	6.642
12.5	-100.0	1500.0	7250.0	.1	200.0	250.0	500.0	5.959	6.642
3.5	-100.0	1900.0	3000.0	.1	200.0	250.0	500.0	48.213	6.642
6.5	-100.0	1900.0	4750.0	.1	200.0	250.0	500.0	14.344	6.642
9.5	-100.0	1900.0	6000.0	.1	200.0	250.0	500.0	8.151	6.642
12.5	-100.0	1900.0	7000.0	.1	200.0	250.0	500.0	6.759	6.642
3.5	0.0	400.0	3750.0	.1	200.0	250.0	500.0	27.995	6.642
6.5	0.0	400.0	5250.0	.1	200.0	250.0	500.0	11.794	6.642
9.5	0.0	400.0	6500.0	.1	200.0	250.0	500.0	5.952	6.642
12.5	0.0	400.0	7500.0	.1	200.0	250.0	500.0	8.837	6.642

VITA

Jack Raymond Lippert was born on 7 December 1951 in Cincinnati, Ohio. He received the degree of Bachelor of Science in Aerospace Engineering from the University of Cincinnati in June, 1974. Upon graduation, he was employed as a project engineer working in the area of aircraft survivability/lightning susceptability for the Air Force Flight Dynamics Laboratory, Wright Patterson AFB, Ohio. He entered the School of Engineering, Air Force Institute of Technology in October 1979. He is a member of Eta Kappa Nu.

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Triggered Lightning
Lightning Testing

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The feasibility of using rocket-triggered lightning as a research and development tool for testing hardware is investigated. Previous experimental work in the area is examined and used as the foundation for the experiments in this thesis to establish the significant factors of a successful lightning-triggering station. Using a point charge model, computer simulations were performed to determine the most probable locations of the charge centers associated with the triggered discharge. Five electric field records obtained

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from field mills were used to perform this simulation. A full scale test technique configuration is proposed for subjecting representative Air Force subsystems and components to the lightning threat. A conclusion is drawn that such a system is feasible at Mt. Baldy, New Mexico with minor augmentations of the existing facilities of the Langmuir Laboratory.

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